In shoe pressure measurement and analysis in relation to FootStrike

Saba Naghipour

Supervisor: Dr. Robert Morley

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Electrical and Systems Engineering Department, School of Engineering and Applied Science,
Washington University in St. Louis

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Abstract

The In Shoe pressure system project is a research effort to reduce running injuries and prevent FootStrike. Despite all the money that has been dispensed into reducing running injuries by designing better shoes, the ideal way to reduce running injuries may be simply to find a way to see the impact force and pressure in different parts of the foot while running. The goal of this project is to display the maximum pressure in different parts of foot while running and to inform the person if they run on their heel. This information is based on the plot of the pressure range of their running for both recorded and real time. The approach is to design a circuit to collect data output from sensors, and then converts the data to pressure.

The application is:

- Footwear research for design
- Compare, screen, and isolate food function
- Identify pressure range for medical purposes and personal running regulation.

Introduction

Running technique has prompted much debate and controversy over the years as to what is the correct way of running. Recently, there has been much research on the biomechanics of running in both kinematics and running kinetics, which describe the relationship between movements and forces while running. Even if running is a good exercise to maintain a healthy body, it can damage bones if people don’t know how to run correctly. First, I give a brief
explanation of what FootStrike is and different types of it. Later, I will divide the procedure to sensor selection criteria, sensor position selection, circuit design, data processing, and data analysis.

**Background**

**Types of FootStrike**
- HeelStrike
- Midfoot Strike
- Forefeet Strike

There are three basic types of FootStrikes: HeelStrike, Midfoot strike, and Forefoot or ToeStrike. The most common type of FootStrike is the HeelStrike and it occurs when a person lands on their heel first, sometimes slapping their foot on the ground while running. Midfoot Strike, which is considered a preferred type of foot strike, is when the person lands with a flat foot. Forefoot Strike or ToeStrike, which is considered to be good, occurs is when the person lands on ball of the foot toward his/her toes. The correct way of running involves the Midfoot and Forefoot Strike, rather than HeelStrike.

**Comparison of various FootStrike effects on the body**

Midfoot strike runners experience less hip injuries, such as IT band syndrome and hip bursitis, than Heelstrike runners. Midfoot strike runners lean forward while running which will help them run faster by boosting their body’s natural forward momentum and work with the force of gravity in a smooth horizontal flow.
HeelStrike runners land in such a way that their leg is directly perpendicular to body motion, versus falling forward into a natural running motion so that the impact force of the heel with the ground causes a significant force to skeletal system. Even though the heel is the hardest bone of the body, it does not absorb the impact force. It combines the gravitational forces with the impact force and compresses it toward the skeleton.

Forefoot Strike causes more of muscle use with less bouncing up and down. Daniel Lieberman, a researcher at Harvard University said, “Forefoot and Midfoot runners land closer to their center of mass than Heelstrike runners, they have seven times less impact force on their bones. Heelstrike can cause a direct force of up to three times more than a runner’s body weight on the feet, ankles, knees and hips between 1000-1500 times per time. In addition to just hip injury, Heelstrikers also may be in risk of suffering from tiny bone fractures, ligament tears or damaged tendons in feet and ankles”.

Here is a great picture of Good FootStrike. The areas that have darker colors are considering the parts that you have to have more pressure than the lighter areas.

Here is great picture of the impact transient force that person have while running on heel (on the left) vs. running on forefoot.

Read more: http://www.livestrong.com/article/553745-the-impact-of-running-sneakers-on-the-foot/#ixzz1rPBjHyRI
Effects of running barefoot or with shoes in relation to foot strikes

Running barefoot generates less impact force on the heel. Barefoot runners are mostly front foot strikers; however runners who have been wearing shoes for ages will still hit the floor with their heel regardless of what kind of shoes they use.

“Running with athletic shoes over the years has adapted our legs and feet to the incidence of a HeelStrike, and adapted the majority of runners into HeelStrikers. The feet of runners land differently, depending on whether one is running in bare feet or in athletic shoes with a big cushion under the heel. The heel cushions and arch supports within modern shoes have made our feet weaker. The foot has so much support in these shoes that the muscles don’t need to work as much as they would otherwise and have grown weak.” said Warden. However, running barefoot may not be a good option for those who have been running with shoes for many years, because running HeelStrike barefoot may cause more injury.

As a result, since foot strike depends on the type of running shoe that we wear, it gives us a hint that maybe one way to change our foot strike is to change the type of shoes we wear. But
in fact most running shoes help to reduce the impact by spreading the force over the foot area. However, they do not remove the impact the force we apply on heel. Recently many runners have switched to Minimalist Running Shoes that are lightweight and flexible. It has a roomy toe box which help to increase the Forefoot and it has minimal in support under the heel.

Even if changing shoes is a good solution, it may not be sufficient because, as was mentioned, after running with a particular shoe for years, there is way of ensuring that changing to minimalist running shoes will correct a way of running. You may still be running on your heel with less support while using minimalist shoes which can cause more injury.

**Design procedure**

*Methods used to get output from running*

My first choice was to use an accelerometer. It seems to be a very smart way because most smart phones have an accelerometer and there is no need to do any additional programing on the phone. We could find the force by using basic formula of $F=ma$, where $m$ is the weight of runner and $a$ is the acceleration that we get from the accelerometer connected to the shoes near the leg. However, later we realized that using accelerometer may not be a good way because even if it gives us the force it will not show if the force is coming from heel or toe or any other parts of the foot.

The second choice was to switch to a sensor. I must find one with the pressure range that work for running purposes. First I decided to use 3000E F-Scan Tekscan pressure sensor with pressure range of 300psi to 2,069kpa. It provides a great picture of foot function and
pressure in more detail because it has over 256 sensors. It also provides a very high resolution, but it required advance equipment and skill beyond my scope of this project.

The final choice was to use individual FlexiForce sensors, which help us to find the pressure of a single point region and the distribution as well. I needed to know where and specific kind of sensor I have to choose.

**Sensor position selection**

There are fifteen areas on the sole foot that support body weight during normal activates. I selected the heel and metatarsal areas to see if a person favors HeelStrike or Forefeet strike. Adding Mid feet and hallux would provide better results but since each amplifier can connect to 4 sensors, and adding two sensors, would force us another amplifier.

**Pressure range and sensor selection**

To be able to estimate pressure range we consider two different cases. Pressure is mass per unit area \( (p=w/A) \) so it bring us to the conclusion that the max pressure is when we have high mass in a very small area. This is the case is when a very heavy person with weight of 300lb lands on his
or her heel which is a very small are something around (1.98in x 1.98in), so it gives us maximum pressure of 76.5 psi.

The minimum pressure is when a very light person with weight of 50lb and a very large plantar surface of (1.9in x 9.84in) lands on the floor with entire foot which gives us minimum pressure of 2.56 psi. So the idea pressure range that we were looking was break down to this chart:

<table>
<thead>
<tr>
<th>Max pressure</th>
<th>Min pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>76.5 psi</td>
<td>2.56 psi</td>
</tr>
</tbody>
</table>

Other than pressure range, our pressures sensors have to have:

- Accuracy within (5%)
- Corrosion and dust resistance
- High sensitivity
- Extremely thin (flexible and easy to adjust in shoe)

Temperature was considered at first but later I realized that the resistance of the sensors only changes 2% for humidity and higher temperature which is negligible. Based on my needs, the FlexiForce sensor was the best match. Then I had to design a circuit that could give me data output from those resistors. Here is the recommended circuit for variable resister:
Now that I know my sensor, I have to find minimum and maximum resistance that it can possibly have. I connect the sensor to the multimeter through the two ending pins to measure the resistance change. I need the resistance range of the sensor to calculate the other parts of the circuits. I got infinite resistance value while applying no pressure and as I increase the applied force I started getting value out of the sensor. As the force increased, the value of the resistor in the sensor decreased. On the data sheet of the sensor, it specifies the resistor of the sensor with no load to be greater than 5MΩ and by applying a large force to the sensor I get the lowest possible value of 0.5MΩ. So now we have the resistance range of the sensor 0.5 MΩ - 5 MΩ.
One way to get output out of FlexiForce sensor is to build a circuit produces voltage. We will use a circuit as shown above using an op-amp to do this. But still I had to find a suitable value for the feedback resistor, $R_f$, which is required in this circuit analysis. Because the highest value of the sensor resistance is $5 \text{ M} \Omega$, the resistor in parallel to the op-amp has to be also at least $5 \text{ M} \Omega$ otherwise the resistor will overheat and burn up the resistor. By simply writing a KCL for the inverting input, we get:

$$I_1-I_2-I_{\text{IN}}=0 \quad \rightarrow \quad I_1=I_2; \quad \frac{\text{Vin}}{\text{Rs}}=-\frac{\text{Vout}}{R_f} \quad \rightarrow \quad \frac{\text{Vout}}{\text{Vin}}=-\frac{R_f}{\text{Rs}}$$

With no pressure,

$$R_s=\text{max}=5\text{M} \Omega \quad \text{then} \quad \frac{\text{Vout}}{\text{Vin}}=-\frac{R_f}{R_s}=-\frac{5}{5}=-1 \rightarrow \text{Vout}=-\text{Vin}$$

With high pressure,

$$R_s=\text{min}=0.5\text{M} \Omega \quad \text{then} \quad \frac{\text{Vout}}{\text{Vin}}=-\frac{R_f}{R_s}=-\frac{0.5}{5}=-10 \rightarrow \text{Vout}=-10 \text{Vin}$$

For Vin,

<table>
<thead>
<tr>
<th>R</th>
<th>$5\text{M} \Omega$</th>
<th>$0.5\text{M} \Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vout</td>
<td>-1*Vin</td>
<td>-10*Vin</td>
</tr>
</tbody>
</table>
If \( V_{in} = -1/2\) volt

<table>
<thead>
<tr>
<th>( R )</th>
<th>5M( \Omega )</th>
<th>0.5M( \Omega )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{out} )</td>
<td>0.5volt</td>
<td>5volt</td>
</tr>
</tbody>
</table>

I get to the conclusion that by applying greater force, the pressure increases and the resistance of the sensor decreases so the voltage increases. The voltage and pressure are proportional, but the resistance is inversely proportional and non-linear to the pressure.

\[ V_{out} = -V_{in}(\frac{1}{R}) = -V_{in}(\frac{1}{0.5M\Omega}) = -V_{in} \]

The output of the op-amp is linearly proportional to the voltage difference between the input \( V^+ \) and \( V^- \) by a factor of gain \( A \). The output voltage is limited to the range \(-vcc < v < +vcc\) where \( vcc \) is the supply voltage specified by the designer of the op-amp. When the output swings to \( Vcc \) the Op Amp is saturated, so \( Vcc = 15v \).
**Cut off frequency**

This not the final design of circuit. There was one more part that I still needed to add to my circuits. If we add a capacitor c in parallel with the feedback resistor, we can reduce the upper frequency cutoff point. If the frequency is low, the capacitors impedance is higher than the resistor, so it does not affect the circuit. At higher frequency, the capacitor impedance is lower than the resistor, so the impedance of the parallel combination limit which means the gain (-Rf/Rs) of the amplifier decrease beyond the cut off frequency. The high-frequency cut off point is the frequency at which the amplifier has fallen by -3 dB and the phase changes by 45 degree.

Adding a capacitor to the circuits helped to remove the noise in my signal but the problem was that I was not sure about the value of my capacitor. The value of capacitor is related to the cut off frequency of the circuit. Signal is the sum of sinusoid so if I see my signal in Discrete Fourier transform I can have a better understanding of my data to choose a better capacitor. I chose to build the circuit without a capacitor and compute the Fourier transform of the frequency component by adding the spectral function to my output to convert voltage to frequency. The X axis is my frequency and the y axis is the amplitude of my signal. Now I can easily compute the noise vs. the actual signal. Looking at my graph, the blue line is my sensor without a capacitor. As we can see from the graph, up to 15Hz all my signals are in good range, but if you look closely and compare the blue line to others you will see that after 15HZ, the blue line starts being a lot higher than others and doesn’t look like the input signal, but more like noise. However, around 30Hz it’s also back to signal and good range, but we care about the smallest possible point so I think 15Hz for the cut off frequency was a good choice. The first picture has the entire signal together but the second picture is a closer look at them. As you look
at the closer picture the green and red kind of flow in a reasonable shape, but blue line does not look like the signal but more look like it has a lot of noise on it.
So that we have the cut off frequency now we can find the value for our capacitor.

Cut off frequency is $W=\frac{2\pi f}{R \times C}$

$$\frac{1}{(50 \times 10^6 \times C)} = 2(3.14) \times (15)$$

$$C = \frac{2(3.14) \times (15)}{(50 \times 10^6)} \approx 2.2 \times 10^{-9} = 2.2 \text{nf}$$

We also gave solved for transfer function:

$$H(S) = \frac{-Z_2}{Z_1} = \frac{-R_2}{1 + S \times C \times R_2} / R_1 = \frac{-[R_1 \times R_2]}{1 + C \times R_2 \times S}$$

$C = jw$ then

$$H(S) = -\frac{Z_2}{Z_1} = -\frac{(R_2/1 + S \times C \times R_2)}{R_1} = -[R_1 \times R_2] / [1 + C \times R_2 \times (jw)]$$

As we can see from Bode plot the cut off frequency experimental value is the same as the theoretical value which is 14.49 ~ 15 rad/s
Experimental result of Cut off frequency
Theoretical result of Cut off frequency
The final design of the circuit ended up as an inverting low-pass amplifier with variable input resistance. Each of the FlexiForce pressure sensors in the insole are connected to a 2.2 nF capacitor in parallel with a 5MΩ resistor, a LA324N Op Amp and grounded through the connector. A -0.5 voltage is input to each of the sensors. The LA324N Op Amp has 14 pins. Pin 1, 7, 8, 14 connect to the voltage output. Pin 2, 6, 9, 13 connect to sensor, resistor, capacitor and negative input. Pin 3, 5, 10, 12 connected to the ground. Pin 4 connected to +15 and pin 11 conected to -15 voltage.
Data processing

Each voltage output is connected to an Elvis board to convert embedded analog to digital (A/D) through channel 0 to 3. Voltage is not what we are looking for, so we have to find a way to convert voltage to pressure. We know that voltage and pressure are proportional by a constant K. I can find K by calibration. Using multiple known masses to come up with voltage for given pressure then the system convert in to linear equation for easier analysis.

The pressure is pounds/ in² is $p = \frac{w}{A}$

By placing two different masses of $m_1 = 1.2\ \text{lb}$ and $m_2 = 5.2\ \text{lb}$ on the sensor, I get $V_1 = 1\ \text{volt}$ and $V_2 = 2\ \text{volt}$.

<table>
<thead>
<tr>
<th>$M_1 = 1.2\ \text{lb}$</th>
<th>$M_2 = 5.2\ \text{lb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1 = 1\ \text{volt}$</td>
<td>$V_2 = 2\ \text{volt}$</td>
</tr>
</tbody>
</table>

The active area of the sensors can be found by the following method:

The diameter of the active area of the sensor is about $D = 9.33\ \text{mm} = 0.375\ \text{in}$ so $r = 0.1875$

$A = \text{area} = \pi r^2 = (3.14)(0.1875)^2 = 0.11039\ \text{in}^2 \quad \rightarrow \quad A = 0.11039\ \text{in}^2$

$P_1 = \frac{m_1}{A} = \frac{2.5}{0.11039} = 22.64698\ \text{lb/ in}^2 \quad \rightarrow \quad P_1 = 22.64698\ \text{lb/ in}^2$

$P_2 = \frac{m_2}{A} = \frac{5.2}{0.11039} = 47.10572\ \text{lb/ in}^2 \quad \rightarrow \quad P_2 = 47.10572\ \text{lb/ in}^2$

$K = \frac{P_2 - P_1}{V_2 - V_1} = \frac{47.10572 - 22.64698}{2 - 1} = 24.45844 \quad \rightarrow \quad K = 24.458$
So the equation of the line is $y=mx+b_0$ which in this case is $p=vm+V_0$

Choosing point $(P_2,V_2)=(47, 2)$ we get $47=2*20+V_0$ solving for $V_0 →$

$V_0=1.81116\text{Volt}$

**Data acquisition**

First, we create a blank VI and DAQ assistant. Then, we created analog input voltage by clicking on Acquire Signal and selecting ai0 to ai3. We gave the signal input range of +/- 10v and terminal configuration of RSE. We used Nyquist principle to find sampling frequency which has to be greater than twice the maximum frequency (2*50=100), otherwise sampling will be too fast or too slow that we either overload or miss data. I chose the acquisition model to be continuous samples and sample to read of 100Hz and sample rate of 100 samples per second. We connected the voltage output to the Elvis board through cable from Ai0+,Ai1+,Ai2+ and AI3+ and we grounded the negative AI0- to AI3-. Now we can extract voltage out and we analyze our data using Labview.

We created a loop to convert the voltage to pressure using Labview functions. So inside the loop we multiple the voltage by the constant $K$ and added the voltage initial to it then we have to convert it to KPa by multiplying by 6896 and dividing by 1000. To make it easier to view the results, we initiated negative values to zero. We chose resulting data type to 2D array of scalars. Now that I have the pressure, I use *write and read* to record and see our data on the graph. The read and write function has a case that the true case is to write and false case is to read. I give it a file name when I record and I run the same file while I try to see the data.
I connect the two stop sign by an OR gate so that we can either stop it by simply clicking on stop on the front panel (on block diagram, it is the stop sign that is connected to the loop.) We can also stop it and prevent it from overloading by simply giving it certain time (on block diagram, it is the stop sign that is connected to the both loop and stop in DAQ.) I can stop it by either simply clicking on stop on front panel (the one is connected to the loop) or stopping it from being overload after certain time (the one is connected to the DAQ and OR gate).
Experimental set up
Final results

*Heel strike*
Forefoot strike
Future work

There are ways to develop and expand this project in the future such as developing a portable technology suitable for outdoor cavities and to solve the discomfort during the exercise. This project can be done by better data acquisition system by using microcontroller and Bluetooth antenna so that instead of the computer, we can use a smartphone as the remote receiver for outdoor activities. Adding additional sensors would also help to reduce the error and make it more accurate.

Conclusion

In shoe pressure measurement system is a very inexpensive and easy way to display the maximum pressure in different parts of the foot and inform the person correct way of running. It can also help in other applications such as footwear research for design, comparison, screening, isolation of foot function and identifying pressure range for medical purpose and personal running regulation.

Acknowledgment

I would like to thank Professor Morley for his help. I am so grateful to Professor Richter, who made this project possible. Many thanks to the Electrical Engineering Department at Washington University for their support.
Reference

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http://www.livestrong.com/article/553745-the-impact-of-running-sneakers-on-the-foot/#ixzz1rPBjHyRI
### Bill of Materials for this design:

<table>
<thead>
<tr>
<th>Part list</th>
<th>Price</th>
</tr>
</thead>
<tbody>
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<td>Package pressure Flexi Force sensor and delivery</td>
<td>$80</td>
</tr>
<tr>
<td>Insole</td>
<td>$20</td>
</tr>
<tr>
<td>Resister (4)</td>
<td>$0.95</td>
</tr>
<tr>
<td>Capacitor (4)</td>
<td>$0.463</td>
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<tr>
<td>Op Amp (1)</td>
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<tr>
<td>Wire Wrapping Wire</td>
<td>$30</td>
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<tr>
<td>7 Conductor Multi-Gauge Wire</td>
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<tr>
<td>Solderable Perf-Board SMALL</td>
<td>$1</td>
</tr>
<tr>
<td>NI ELVIS BOARD</td>
<td>$3,499</td>
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